

EOS Terra

**Mission Status
at
Earth Science
Constellation
MOWG Meeting
@ Boulder, CO
April 13th, 2016**



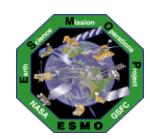
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Terra Mission Director - Code 428

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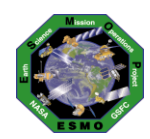
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Topics



- **Mission Summary**
- **Spacecraft Subsystems Summary**
- **Recent & Planned Activities**
- **Inclination Adjust Maneuvers**
- **Conjunction History**
- **Propellant Usage & Lifetime Estimate**
- **End-Of-Mission Plan**
- **Summary**
- **Additional Slides:**
 - Orbit Maintenance Maneuvers
 - Ground Track Error & Mean Local Time History
 - MLT History
 - EPS Performance and Improvements

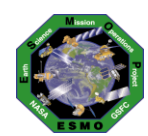


EOS Terra Mission Summary



- **Mar 2015:** Mission Extension Senior Review Proposal Panel Report
 - Mission extension through **FY20**
 - Senior Review submission delivered in Mar 2015
- **2015-16** Inclination Adjust Maneuvers
 - Fall 2015 Inclination Maneuvers
 - **IAM #42 - October 28th**
 - Spring 2016 Inclination Maneuvers
 - **IAM #43 - February 18th**
 - **Aborted – Terra to Safehold**
 - **IAM #44 – March 3rd**
 - **IAM #45 – March 11th**
 - Fall 2016 Inclination Maneuvers
 - **IAM #46 – Oct 2016**
- **12/18/15:** Terra 16-Year Anniversary
 - 5-Year Design Life, 6 year goal
 - Reliability Estimates thru 2020+
 - Consumables through 2017+
- **Jan/Feb 2016:** EOS Flight Operations Annual Review #9





Terra Mission Overview

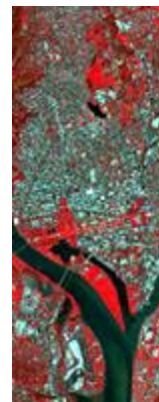


Terra Features

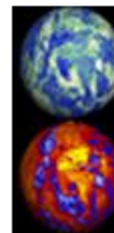
- **Launch Date:** December 18, 1999 (Atlas IIAS, VAFB)
- **Orbit:** 705 km, Sun-synchronous polar, 98.2° Inclination, 10:30 AM MLT descending node
- **Instrument Payload:**
 - **ASTER (SWIR, TIR & VNIR)** - Advanced Spaceborne Thermal Emission and Reflection Radiometer (Japan)
 - **CERES (Fore & Aft)** - Clouds and the Earth's Radiant Energy System (USA – Langley)
 - **MISR** - Multi-angle Imaging Spectro-Radiometer (USA – JPL)
 - **MODIS** - Moderate Resolution Imaging Spectro-radiometer (USA – GSFC)
 - **MOPITT** - Measurement of Pollution in the Troposphere (Canada)
- **Project Management:** Earth Science Mission Operations (ESMO)
- **Spacecraft Flight Operations:** Contracted by GSFC to Honeywell / ASRC/Aerotek/AIMM team and supported by NASA NENs and TDRSS
- **Instrument Operations and Science Data processing:** Performed at respective Instrument Locations where developed
- **Mission Duration:** Successfully completed Prime mission of 5 years. Currently in Extended Operations.
- **Distributed Active Archive Centers:** LP DAAC – MODIS, ASTER; Langley DAAC – CERES, MISR, MOPITT

Science

- The primary objective of the Terra Mission is to simultaneously study clouds, water vapor, aerosol, trace gases, land surface and oceanic properties, as well as the interaction between them and their effect on the Earth's energy budget and climate.



ASTER



CERES



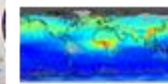
Terra (EOS AM-1)



MODIS

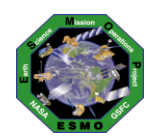


MISR



MOPITT



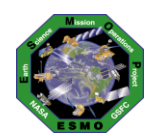


Terra Spacecraft Status

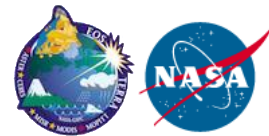


All subsystems on Primary Hardware except as noted

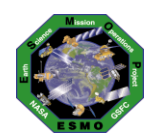
- **Command & Data Handling (CDH) – Nominal**
 - Solid State Recorder (SSR) – holds ~1 orbit of data
 - 10 of 58 SSR Printed Wire Assembly tripped off resulting in reduced recording capacity
- **Communications (COMM) – Nominal**
 - DAS Modulator Failure on 05/29/2008 (Operating on Redundant)
 - Use K-Band primarily, X-Band as needed for Science Playback
- **Electrical Power System (EPS) – Good**
 - Battery Cell and Heater Controller Anomaly (10/13/2009)
 - 1 of 24 Solar Panel Failed (9/24/2000)
- **Flight Software (FSW) – Nominal**
- **Guidance, Navigation & Control (GN&C) – Nominal**
 - Minor loss of sensitivity in SSSTs – updated tracker biases to compensate
- **Propulsion (PROP) – Nominal**
- **Thermal Control System (TCS) – Nominal**
- **Instruments (INST) – Nominal**
 - Only ASTER SWIR failed, all other instruments are taking science



Spacecraft Component Status



Subsystem	Component	Design	Current	Capability	Comments
EPS	Solar Array	24 Shunts	23 Shunts	96%	Degradation is minimal. Fully capable of supporting mission thru 2020 unless future failures occur
	Batteries	108 Cells	107 Cells	99%	BBAT cell #50 failed on 10/15/09.
	Batteries	36 Heater Controls	28 Heater Controls	77%	BBAT heater control failed on 4 of 9 heater groups on primary, redundant, and survival. Battery cell charging/discharging and the remaining heater groups are preventing cells from freezing. PBAT heater control performance is nominal.
TCS	MOPITTCPHTS	2	2	Full	Performance is nominal
	SWIR CPHTS	2	2	Full	Performance is nominal
	TIR CPHTS	2	2	Full	Random temperature fluctuations. Performance within requirements.
SCC	SCC	2	2	Full	Performance is nominal
COMM	HGA	2	2	Full	MDA BITE failures occur 2-3/week due to SEU. Recoverable
	X-Band	2	1	75%	DAS Modulator 1 failed (50%). Solid State Power Amplifier redundancy still available (100%).
	CTIU	2	2	Full	Performance is nominal
	OMNI	2	2	Full	Performance is nominal
CDH	MO	2	2	Full	Drift rate changes have occurred since 10/3/10. Performance is within requirements.
	SFE	2	2	Full	SFE SEU occur 1-2/year. Recoverable
	SSR	59 PWA	49 PWA	83.1%	Recycle of Data Memory Unit likely to recover all Printed Wire Assemblies
GNC	IRU	3	3	Full	Performance is nominal. 2 for 3 redundancy
	TAM	2	2	Full	Performance is nominal
	SSST	2	2	Full	Minor loss of sensitivity in SSSTs – tracker biases updated
	CSS	2	2	Full	Performance is nominal
	ESA	2	2	Full	Performance is nominal
	FSS	1	1	Full	Performance is nominal. Not currently used
	RWA	4	4	Full	Performance is nominal. 3 for 4 redundancy
	MTR	3	3	Full	Performance is nominal
Prop	REAs	16	16	Full	Performance is nominal
Instruments	ASTER - SWIR	2	2	0%	Cooler is unable to maintain detector temperature. Science Data is unusable (Fully Saturated) and is no longer being recorded. Still collecting and monitoring Engineering data.
	ASTER - TIR	2	2	Full	Performance is nominal
	ASTER - VNIR	2	2	Full	Performance is nominal
	CERES - Aft	1	1	Full	Performance is nominal
	CERES - Fore	1	1	Full	Performance is nominal
	MISR	2	2	Full	Performance is nominal
	MODIS	2	1	50%	Power Supply #2 failed, Formatter A degraded, cross-strapped. All Science is nominal.
	MOPITT	2	1	50%	Displacer B and Chopper Motor failed. Loss of redundancy only. All Science is nominal.



Recent Activities



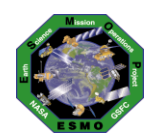
• Propulsive Maneuvers

- Drag Make Up Maneuver (DMU) #93 on 06/16/15
 - Debris Avoidance Maneuver (DAM) #10
- Drag Make Up Maneuver (DMU) #94 on 09/29/15
 - Reduced Duty Cycle (25%) #1
- Inclination Adjust Maneuver (IAM) #42 on 10/28/15
- Drag Make Up Maneuver (DMU) #95 on 12/17/15
 - Reduced Duty Cycle (25%) #2
- Inclination Adjust Maneuver (IAM) #43 on 02/18/16
 - Aborted due to incorrect slew direction/Terra to Safehold
- Inclination Adjust Maneuver (IAM) #44 on 03/03/16
- Inclination Adjust Maneuver (IAM) #45 on 03/11/16
- Drag Make Up Maneuver (DMU) #96 planned 04/14/16

• Calibration Maneuvers

- MODIS Roll #152 executed on 06/06/15
- MODIS Roll #153 executed on 07/06/15
- MODIS Roll #154 executed on 08/04/15
- MODIS Roll #155 executed on 09/02/15
- MODIS Roll #156 executed on 10/01/15
- MODIS Roll #157 executed on 10/31/15
- MODIS Roll #158 executed on 11/30/15
- MODIS Roll #159 executed on 12/29/15
- MODIS Roll #160 executed on 01/28/16

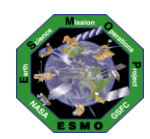
- 06/02/15 – 06/04/15: Constellation MOWG @ GSFC Greenbelt, MD
- 06/30/15: Leap Second #36
- 07/17/15: ASTER TIR Blackbody Heater Anomaly
- 07/24/15: Master Maneuver TMON Uplinked
- 08/12/15: Maneuver TMON On-orbit FSW Demo
- 08/20/15: PBAT C/D Ratio change from 1.04 -> 1.03
- 09/20/15: SFE Off Anomaly (TMON 16 Successfully Recovered)
- 12/18/16: Terra 16th Launch Anniversary (12/18/1999)
- 01/27/16: EOS 2015 Annual Review
- 02/02/16: Terra Lunar Deep Space Calibration Full Team Simulation
- 02/09/16 – 02/11/16: ASTER Interface Meeting
- 02/22/16-03/02/16: Safehold Mode Recovery Activities



Future Plans



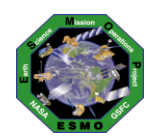
Upcoming Activities	
Terra Full Team LDSC Simulation	02/02/16
Terra Inclination #43 Simulation	02/08/16
ASTER Interface Meeting @ GSFC	02/09/16 – 02/11/16
Terra LUR SSR Automation	March 2016
IAM #43	02/18/16
IAM #44	02/25/16
Terra Senior Review Science Panel (Boulder, CO)	03/29/16 – 03/31/16
Constellation MOWG (Boulder, CO)	04/13/16 – 04/15/16
Update Drag Scale Factor	4Q2016
SA adjusts TMON patch	3Q2016
HGA Model/Keyhole Unwind; MMS Dev - HGA Gimbal motor sun exposure model	3Q2016



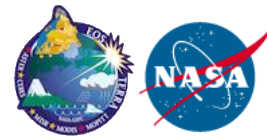
Inclination Adjust Maneuvers



- **Inclination Adjust Maneuvers used to maintain nominal spacecraft mean local time (descending node) of 10:30 AM**
 - 02/18/2016 IAM #43 (320 sec burn) - ABORTED
 - 03/03/2016 IAM #44 (320 sec burn)
 - 03/11/2016 IAM #45 (320 sec burn)
 - Oct 2016 IAM #46 (320 sec burn)
- **Current predictions indicate need to perform 3 maneuvers per year**
 - (2 in Spring, 1 in Fall) to maintain 10:30am +/- 1 minute goal



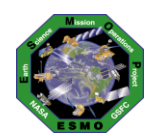
Terra High Interest Events



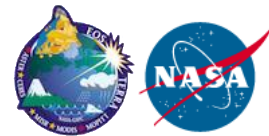
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2015 (T1-T4)	5	2	4	5	3	4	2	0	0	3	1	4	33
Tier 3	2	0	0	1	1	0	0	0	0	0	0	0	4
Tier 4	1	0	0	0	1	1	0	0	0	0	0	1	4
2016 (T1-T4)	1	2											3
Tier 3	0	0											0
Tier 4	0	0											0

CARA Defines the 4 Tiers as: T1 – Notify (email/phone), T2 – Conduct Briefing, T3 – Plan Maneuver, T4 – Execute Maneuver

- **2005:** 4 HIEs – 1 Debris Avoidance Maneuver (DAM) performed on 10/21/2005: Terra vs. 14222 CA on 10/23
- **2006:** 1 HIE – 1 maneuver waived off due to CA. Maneuver originally planned for 01/12/2006: Terra vs. 1716 CA on 1/12 @ 17:46z
- **2007:** 4 HIEs – 1 DAM performed on 06/22/2007: Terra vs. 31410 CA on 6/23
- **2008:** 2 HIEs – 1 DAM planned and waived off: Terra vs. 82832 CA on 10/28/2008 @ 06:17z
- **2009:** 2 HIEs – No DAMs planned or performed
- **2010:** 5 HIEs – 1 DAM performed on 01/22/2010: Terra vs. 34700 CA on 1/23 @ 20:46z
- **2011:** 20 HIEs – 2 DAM planned and waived off: (1) Terra vs. 26181 CA on 3/28/2011 @ 12:14z (2) Terra vs. 30440 Repeating CA 05/07-09/2011
- **2012:** 19 HIEs – 1 maneuver waived off due to CA. Maneuver originally planned for 05/31/2012: Terra vs. 37789 CA on 6/1 @ 22:49z
- **2013:** 17 HIEs – 7 that required significant action
- **2014:** 24 HIEs – 6 that required DAM execution or nominal maneuver waive-off and replan
- **2015:** 33 HIEs – 8 that required DAM execution or nominal maneuver waive-off and replanning
- **2016 thru present:** 3 High Interest Events (HIEs) – 0 that required DAM execution or nominal maneuver waive-off and replanning



Lifetime Fuel Estimates

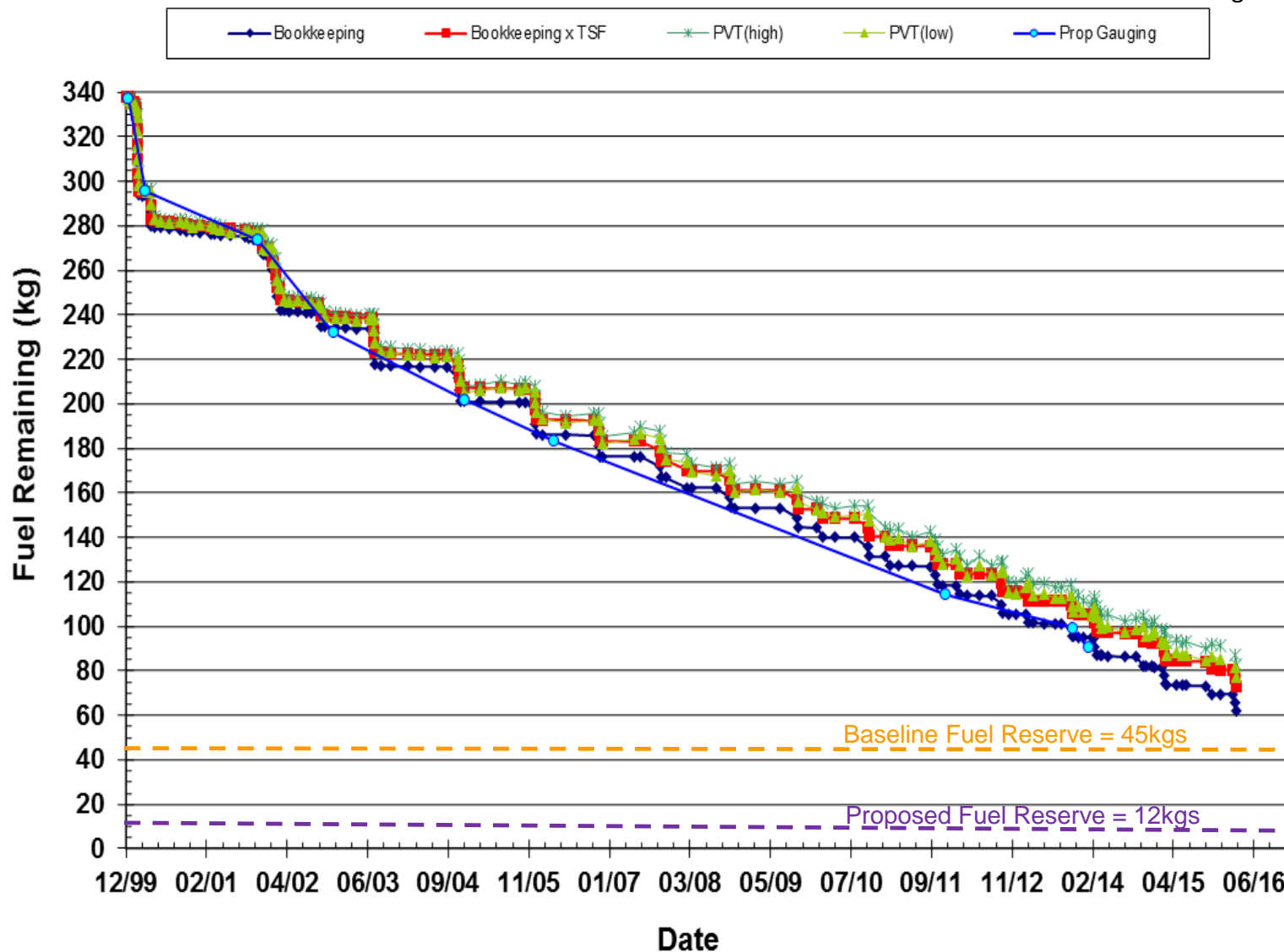


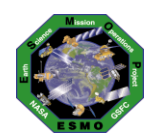
Terra Fuel Usage Comparison

Fuel Usage Approximations:

~4 kg of fuel for every IAM

~0.15 kg of fuel for every DMU

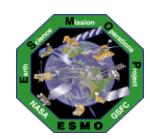




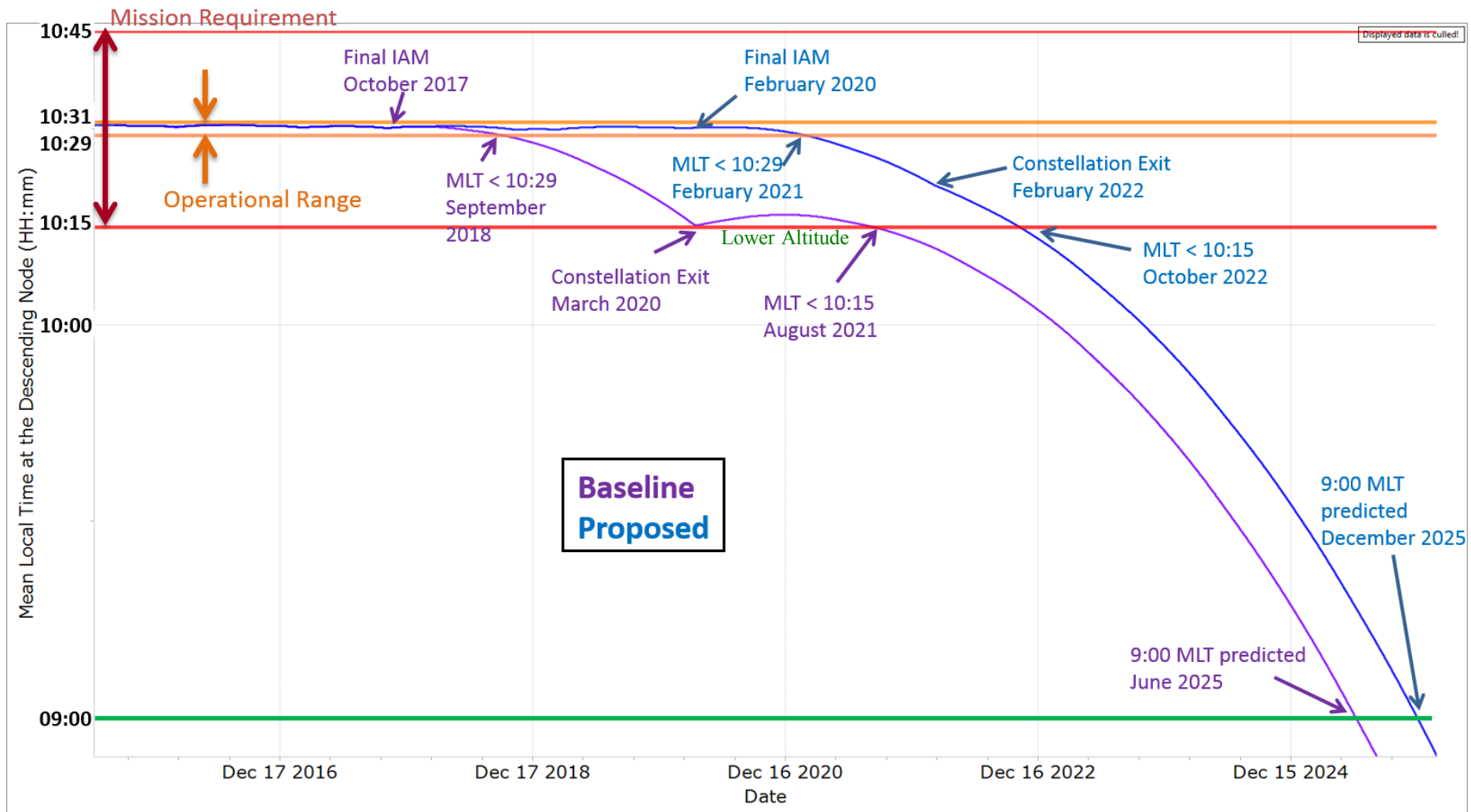
Baseline (19 km) vs. Proposed (4 km) Plan Origin



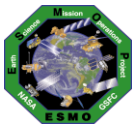
- **Baseline Plan (19km)**: Based on the **2010** definition from the **Afternoon Constellation Operations Coordination Plan**:
 - “The **apogee** of a spacecraft that has exited the constellation must be at least **2 kilometers below the minimum perigee** of all current constellation members.”
 - To effectively exit the Constellation, exited spacecraft’s maximum apogee must be lowered below **692 km**, which is **19 km** below constellation members’ maximum apogee
- **Proposed Plan (4km)**: Based on the **2015 Constellation Coordination Plan** recently signed by all member missions:
 - Safe constellation exit is defined by being completely **outside** the constellation “envelope”
 - To effectively exit the Constellation, exited spacecraft’s maximum apogee will be at least **4 km** below constellation members’ maximum apogee



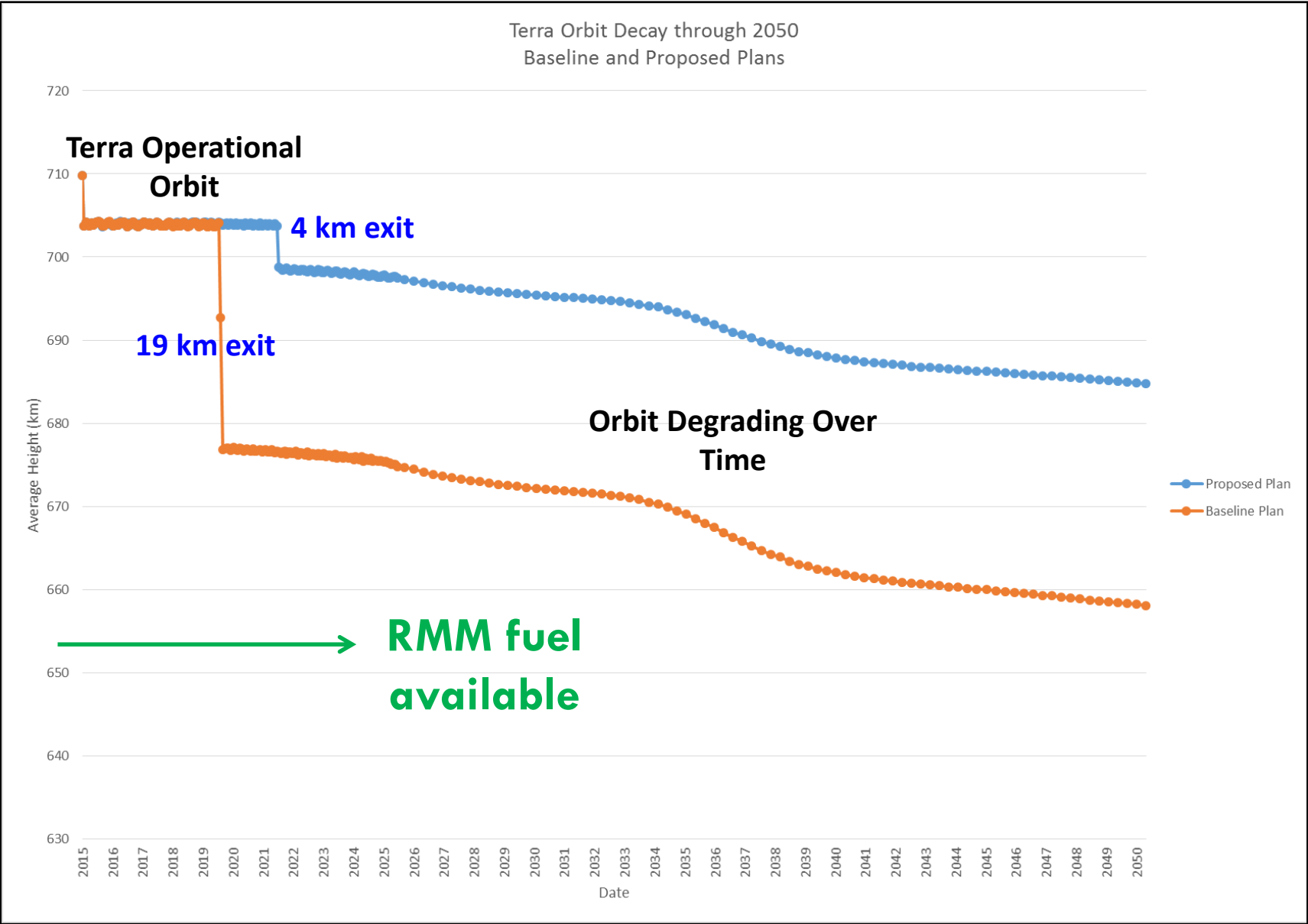
Baseline vs. Proposed Constellation Exit Plan (MLT)

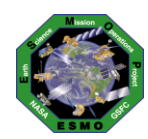


- Difference in **overall mission lifetime** between baseline and proposed plan is **5 months**
- Difference in **science collection** is **additional ~3years** at tight MLT and current altitude
 - **RMM fuel would be maintained throughout the mission lifetime**



Long-Term Orbit Altitude





Terra End-of-Mission Plan



Document Status

- End-of-Mission Plan Document has been revised and submitted along with corresponding waivers to NASA HQ

Content

- Terra will continue normal operations through **October 2020**
- Once all non-reserved fuel has been used, MLT will be drifted to 10:15 AM
- **Feb-Oct 2022**, Terra will use remaining fuel to exit constellation
- Plan is consistent with the **revised Afternoon Constellation (A-Train) Operations Coordination Plan**
- **Pending NASA HQ Decision**

Earth Science Mission Operations Project

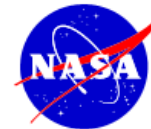
428-PLAN-002

EOS-Terra End of Mission Plan (EOMP)

Revision C

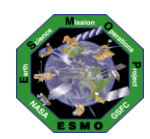
March 2015

Expires: March 2017



GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

Check Configuration Management EOS Tool at <https://cpa1-cm.cms.nasa.gov/cm2/> to verify that this is the correct version prior to use.

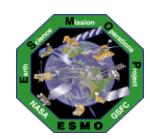


Waiver Details and Status



- Three Waivers have received all required Goddard signatures and are at NASA HQ along with revised EOMP
- Waivers Submitted
 1. **Orbital Lifetime** -> increases by **~13** years (**2065** to **2078**); **25 year requirement**
 2. **Large object collision** -> risk increases from **0.83%** to **1.13%**; **0.1% requirement**
 3. **Reentry Risk** -> risk of injury to the public goes from **1:1463** to **1:1401**
 - Slight increase; Both exceeds the **requirement of 1:10,000**
- **Content of waivers and debris analysis results present at last Constellation MOWG in June 2015 and in Senior Review Proposal submission**
- **Terra Science Team Meeting held on March 29th-30th, 2016**
 - **Goal of determining the impact of Terra Science profile shift (MLT & altitude change)**
 - **Conclusion of team will be presented in form of a report to NASA HQ**
- **NASA HQ will weigh the debris risk against the science & cost benefit and make final decision**
 - Waiver approval required to continue Terra climate observations not science
 - Either scenario takes mission to 2025
 - Debris risk needs to be considered in light of alternatives
 - New mission launched in same orbit will add same or greater risk minus the well maintained science record & well calibrated instruments

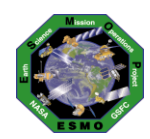




Summary

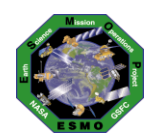


- **Terra remains very healthy 15+ years into the mission**
 - Electrical Power Subsystem performance has been stabilized following 2009 anomaly
 - Fuel Remaining to continue operations to 2020 and beyond
- **Data Capture percentages continue at ~100%**
- **Collision Avoidance events are increasing in frequency**
- **FOT continues to monitor all trends/anomalies**
- **Mission Operations continues to come up with new ideas/process improvements to maximize mission life and efficiency**
- **End of Mission Plan yet to be finalized**
 - **3rd option may need to be developed based on science team conclusions**



Additional Slides

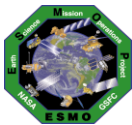
- Orbit / Inclination / MLT Maintenance
- WRS Ground Track Error
- EPS Performance



Orbit/Inclination/MLT Maintenance



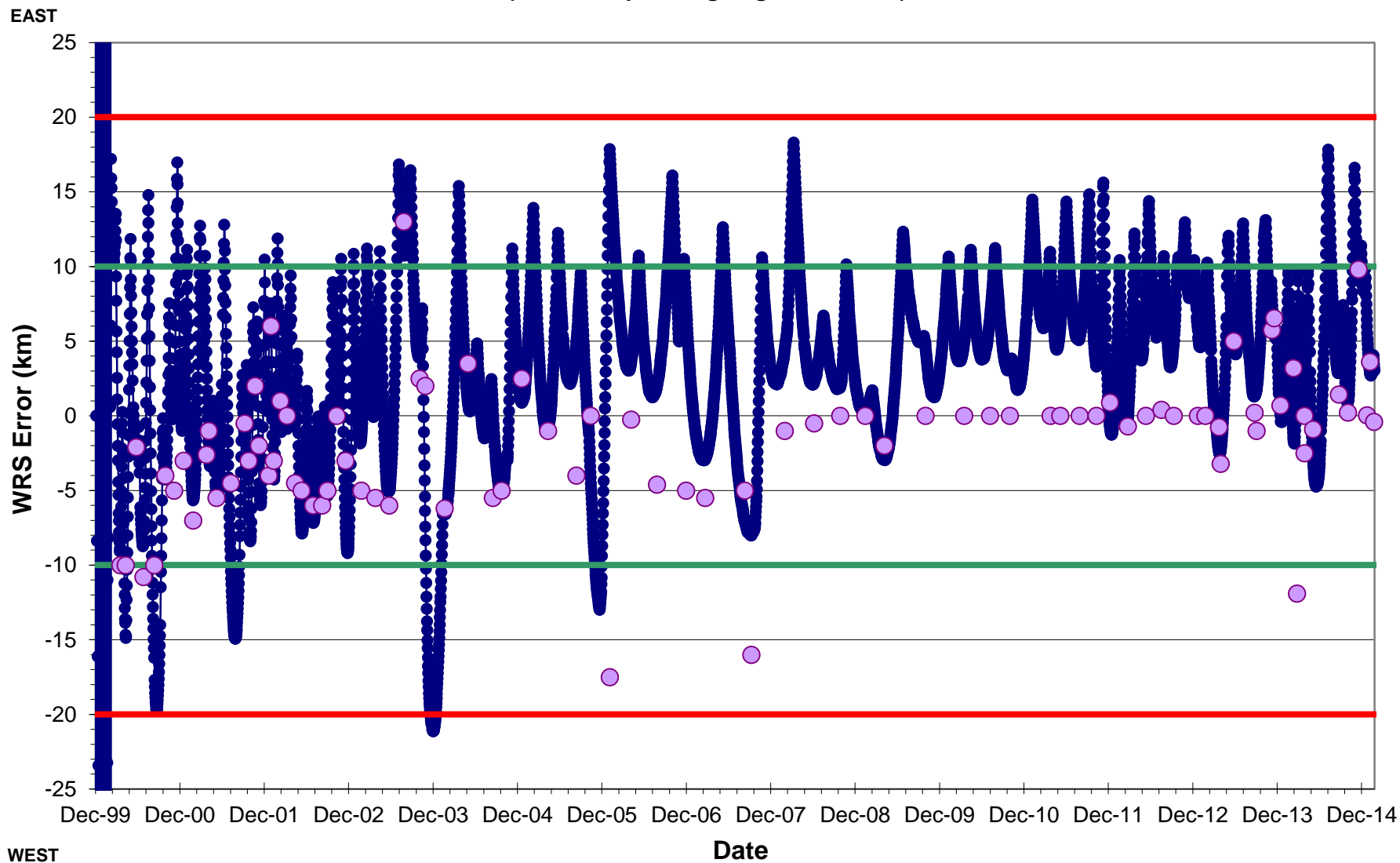
- **Requirement:** Mean Local Time (MLT) maintained between 10:15 and 10:45 measured at the Descending Node.
- **Goal:** Maintain Terra mean local time of the descending node (MLTDN) below 10:31.
- **Constraint:** OCO-2 has requested Terra maintain a MLT less than 10:31 for the duration of its lifetime to maintain a safe separation at the poles.
- **Requirement:** Maintain WRS-2 ground track error, 0 +/-20 km.
- **Requirement:** Maintain Frozen orbit with Argument of Perigee at 90 degrees +/-20 and Eccentricity of 0.0012 +/- 0.0004.
- **Constraint:** Maximum burn duration limited to 320 seconds by spacecraft manufacturer. Complete yaw slews and inclination maneuvers during spacecraft orbital night. Maneuver close to spring and fall equinox to maximize efficiency.

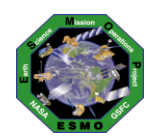


WRS Ground Track Error (GTE)



TERRA WRS Groundtrack Error at the Descending Node
(Maneuver planning targets included)

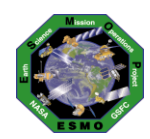




EPS Subsystem Performance



- **Bus Load: Nominal**
 - Average bus load: 2303 Watts
 - Average housekeeping current: 11.89 A
 - Total instrument current: 7.098 A
- **Battery Performance: Nominal with exception of anomalous BBAT condition**
 - BBAT cell # 50 failed following IAM #24 on October 13 (DOY 286) 2009
 - BBAT Voltage Temperature curve changed to better reflect a failed cell
 - BBAT heater control electronics (HCE) anomaly occurred following IAM #24 on October 13 (DOY 286) 2009
 - Performed soft reset, power cycle, switching to redundant side and re-enabling one of the nonfunctioning heater groups to recover HCE functionality without success
 - At least 4 of 9 BBAT heater groups are no longer being controlled
 - Heater control setpoints to changed for controllable heater groups to reduce the thermal gradient
 - PBAT Charge/Discharge Ratio was reduced from 105% to 104% on April 25, 2013 in an effort to extend PBAT life
 - PBAT BPC Channel A Disabled January 14, 2014; increases BBAT cold temperatures due to increased discharge
 - PBAT Charge/Discharge Ratio was reduced from 104% to 103% on August 20, 2015 in an effort to extend PBAT life
- **Battery Temperatures: Nominal with exception of anomalous BBAT data**
 - PBAT and half of BBAT Battery temperatures are regulated by flight software to $\approx -1^{\circ}\text{C}$ to -5°C
 - Almost half of BBAT cell temperatures are below normal (but stable) in the -5°C to -13°C range
- **Battery Voltages (BBAT)**
 - Minimum battery voltages at 66.21 Volts
- **Solar Array**
 - Last offset adjustment performed on Dec 11th 2015
 - Average drift rate for the month, +0.12 deg/day
 - Present offset drift rate is increasing
- **BBAT Cell with Lowest Temperature (excluding Cell #50)**
 - Cell # 19/20/21 : -10.93°C
 - Thermal Gradient(avg): 7.65°C



Questions